Geografia Fisica e Dinamica Quaternaria
GFDQ 46 (2023), 135-151
DOI 10.4454/23dce671

Cynthia Victoria SASSENROTH[1], Maria Cristina SALVATORE[1,2,*], Ernst HAUBER[3], Tilman BUCHER[4], Carlo BARONI[1,4]

Geomorphological map of Kvadehuksletta, Brøggerhalvøya (Svalbard, Norway)

Abstract: Sassenroth C., Salvatore M.C., Hauber E., Bucher T., Baroni C., *Geomorphological map of Kvadehuksletta, Brøggerhalvøya (Svalbard, Norway).* (IT ISSN 0391-9838, 2023). We present a detailed geomorphological map of Kvadehuksletta at the scale of 1:8000, a strandflat on the north-western tip of the Brøgger peninsula in western Spitsbergen. The map is based on remote sensing data and shows how marine, fluvial, glacial, lacustrine, and periglacial processes left their traces in the geomorphological record. Integrating multiple sources of remote sensing data, including satellite imagery and digital elevation models, the map provides a detailed overview of landscape geomorphology and evolution. The map shows the dynamic nature of the region's geomorphological processes, revealing a diverse range of landforms such as sequences of marine beach deposits, fluvial channels, different types of patterned ground, and other features common to polar beach environments. The map highlights the relative chronology of the prominent beach deposits and provides insights into their formation. Remnants of subglacial meltwater channels are also present in the area and represented in the map. Our results underscore the complex interplay between different processes in shaping the current polar beach environment and contribute to our understanding of the broader geomorphological and environmental history of the region. Moreover, the investigated area is interesting for Mars analogue studies, as the polygonal patterned ground and investigations of cryopegs can enlighten the analysis of Martian permafrost landscapes, possible subsurface ice reservoirs, and their potential for human settlements.

Key words: Geomorphological mapping, Polar coastal geomorphology, Holocene raised beaches, Permafrost, Cryopegs, Svalbard.

Riassunto: Sassenroth C., Salvatore M.C., Hauber E., Bucher T., Baroni C., *Carta Geomorfologica del'area di Kvadehuksletta, Brøggerhalvøya (Svalbard, Norvegia).* (IT ISSN 0391-9838, 2023). In questo lavoro presentiamo una carta geomorfologica ad alta risoluzione in scala 1:8000 di Kvadehuksletta, una bassa area costiera al margine nord-occidentale della penisola di Brøgger, nello Spitsbergen occidentale. La carta, basata sull'impiego di dati telerilevati, evidenzia le forme e i depositi connessi ai processi marini, fluviali, glaciali, lacustri e periglaciali che agiscono e hanno agito nel modellamento del rilievo. Integrando diverse fonti di dati remoti, tra cui immagini satellitari e modelli digitali di elevazione (DEM), la carta fornisce una dettagliata rappresentazione della geomorfologia dell'area studiata, offrendo anche molti elementi utili alla ricostruzione dell'evoluzione del rilievo. La carta evidenzia la natura dinamica degli agenti morfogenetici che hanno agito in questa regione artica, rivelando una gamma molto diversificata di forme del rilievo, quali sequenze di depositi marini, alvei e conoidi fluviali, diversi tipi di suoli di origine periglaciale e altre forme proprie degli ambienti polari. Viene evidenziata la cronologia relativa dei principali depositi costieri necessaria per la ricostruzione delle principali fasi della loro evoluzione. I risultati ottenuti sottolineano la complessa interazione tra diversi agenti morfogenetici nel modellamento dell'attuale ambiente di spiaggia polare e contribuiscono alla comprensione della storia geomorfologica e ambientale della regione. Inoltre, l'area di studio è molto interessante in quanto può rappresentare un analogo di forme del rilievo presenti sul pianeta Marte. In particolare, le forme del rilievo associate al permafrost individuate nell'area studiata e le indagini sulle brine ultrasaline (*cryopegs*) localmente presenti, possono contribuire a meglio indirizzare l'analisi delle forme del rilievo di Marte, l'individuazione di possibili serbatoi di ghiaccio al di sotto della superficie marziana, oltre alla caratterizzazione di siti chiave, anche in vista di un loro possibile utilizzo per insediamenti antropici.

Termini chiave: Cartografia geomorfologica, Geomorfologia costiera polare, Spiagge emerse oloceniche, Permafrost, *Cryopegs*, Svalbard.

[1] *Dipartimento di Scienze della Terra, University of Pisa, Via S. Maria 53, 56126, Pisa, Italy.*
[2] *Istituto di Geoscienze e Georisorse, Consiglio Nazionale delle Ricerche, Pisa, Italy.*
[3] *German Aerospace Center (DLR), Institute of Planetary Research, Rutherfordstraße 2, 12489 Berlin.*
[4] *German Aerospace Center (DLR), Institute of Optical Sensor Systems, Rutherfordstraße 2, 12489 Berlin.*
* *Corresponding author: Maria Cristina Salvatore (mariacristina.salvatore@unipi.it)*

INTRODUCTION

Arctic coasts are fragile and rapidly changing landscapes that are particularly sensitive to climate change (Irrgang *et al.*, 2022). The coastal plain of Kvadehuksletta on the western coast of Spitsbergen (Norway) is a prime example of a region that has been shaped by a complex interplay of various geomorphological processes, including coastal, fluvial, glacial, and periglacial ones. It offers a unique opportunity to study the complex landscape assemblage of raised beach complexes in the Artic and its evolution over time.

Detailed geomorphological maps are essential tools to study such landscapes and the processes that shaped them. In a rapidly changing environment, such maps also document the state of a landscape at a given time and are therefore important for comparisons with earlier and later stages of their evolution (Kavan, 2020).

Among the geomorphological maps covering the Kvadehuksletta plain and neighbouring area, worthy of note is the one realised by Carado (1969) for the entire Brøgger peninsula at a scale of 1:50,000. A more detailed map was published by Tolgensbakk and Sollid (1987) who realised the geomorphological map of Kvadehuksletta area at a scale of 1:10,000. The map is very detailed and nicely shows the distribution of the main landscape features, e.g. marine deposits, fluvial landforms, and patterned ground. More recently, Berthling *et al.* (2020) realised a geomorphological map along the Kongsfjorden in north-western Svalbard (Ny-Ålesund and Blomstrandøya area). In particular, the geomorphological map of Ny-Ålesund at the scale of 1:15,000 depicts a wide range of landscape features due to glacial, periglacial, gravitational, fluvial, and coastal processes. The legend adopted distinguishes superficial deposits of different origins using various opaque colours and symbols to describe landforms due to different genesis. In this study, we present a detailed geomorphological map of Kvadehuksletta at a scale of 1:8,000. The map is the result of an extensive interpretation of remotely sensed data from various sources, including satellite images, aerial colour orthophotos, and digital elevation models (DEM) verified by means of field checks. The map identifies and characterises erosional landforms and deposits correlated to recent and past coastal, fluvial, glacial, and periglacial activities. The geomorphological map here presented is a unicum for the area in terms of structure of the map and of the legend adopted. The detailed mapping of Kvadehuksletta provides an essential tool for understanding the region's dynamic landscape and can serve as a basis for comparison to other raised coastal areas on Svalbard and in other Arctic and Antarctic regions.

Overall, the detailed geomorphological map of Kvadehuksletta presented in this study provides a valuable resource for researchers interested in understanding the complex interplay of geomorphological processes in Arctic landscapes.

STUDY AREA

The strandflat of Kvadehuksletta is situated on the north-western tip of the Brøgger peninsula at the western coastline of Spitzbergen (fig. 1), the largest island of the high Arctic Svalbard Archipelago. It is a coastal lowland with sequences of well-preserved beach ridges, which have

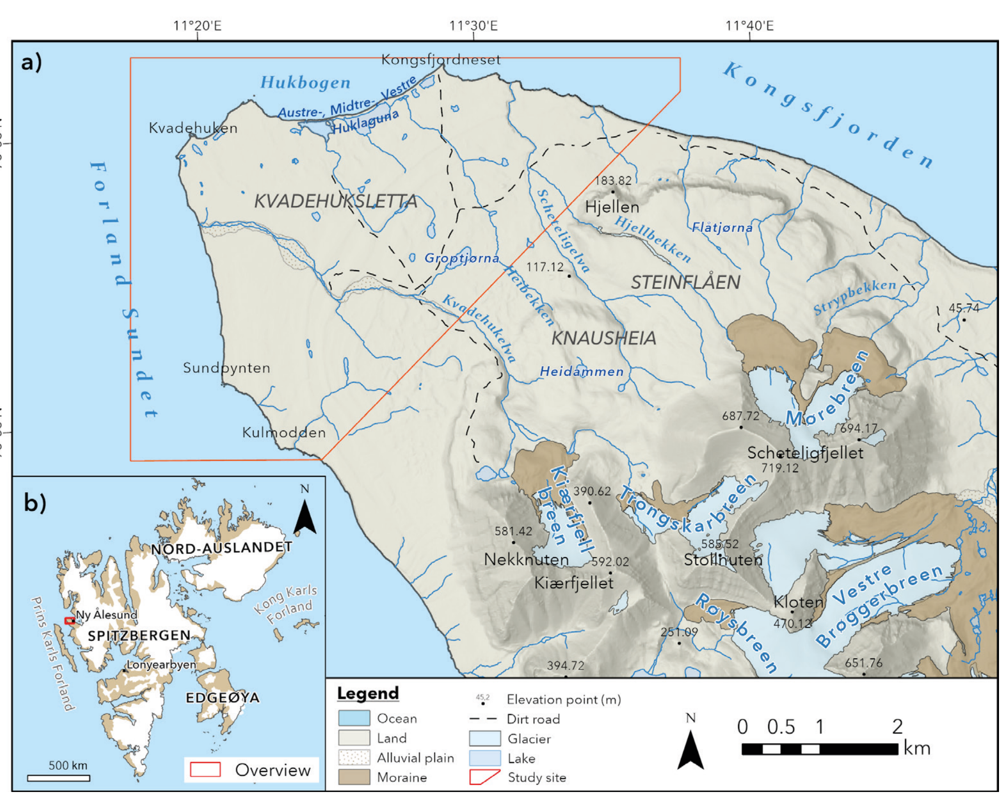

Figure 1 - a) Regional topographical map of NW Brøggerhalvøya, indicating the study site extent (Datasource of the vector dataset and terrain model: Norwegian Polar Institute). b) Overview map of Svalbard (Vector data source: ESRI).

been raised during the Eemian, Late Weichselian and the Holocene (Forman *et al.*, 1987; Etzelmüller, Sollid, 1991). In the north-east, Kvadehuksletta is delimited by the Kongsfjorden, which is one of the largest fjords on the western coast of Spitzbergen. The south-western shore is bounded by the Forlandsundet, which separates Spitzbergen in the east from the Prins Karls Forland in the west. The hinterland of the strandflat is bounded by the topographic plateaus of Knaushaia and Steinflåen, which build the foreland to the peaks in the interior of the Brøgger peninsula, Nekknuten in the southwest, Scheteltigfjellet in the east and Stollnuten peak in between. The three small glaciers of Kjærfjellbreen, Trongskarbreen and Morebreen are hosted in cirques outlined by well-defined arêtes connecting the summits of this mountain range. The glaciers provide a constant meltwater source throughout the summer, by which the two main rivers crosscutting the strandflat are fed. The largest river is Kvadehukselva in the west and Schelteligelva in the east. Several other, smaller channels exist, which are mainly fed by the snowmelt during spring and emerge from smaller local depressions between the major beach ridges. Many of them are not active throughout the whole year and become dry after the melting season.

There are no long-term climatic data that were measured directly at Kvadehuksletta. The closest weather station is located approximately 10 km fjord-inwards from the study site near the research station of Ny-Ålesund (fig. 2). Therefore, the local conditions on Kvadehuksletta may differ from that of the more inland conditions at Ny-Ålesund. Considering the 30-year period 1990-2022, available data from the Norwegian Centre for Climate Services (https://seklima.met.no/observations/, last access 24.11.2023) indicate that the average annual air temperature is approximately -5.1 °C, with the average maximum temperature of 5.4 °C in July and the minimum temperature of -12.7 °C recorded during the polar night in February. The mean annual precipitation amounts to 412 mm, the average precipitation maximum is reached in September with 46 mm, whereas in May the precipitation is lowest with an average precipitation of 17 mm. The low temperatures and minimum precipitation rates throughout the year classify the region of Kvadehuksletta as a polar desert with oceanic influence.

The shore of Kvadehuksletta is nowadays ice-free during almost the whole year (Pavlova *et al.*, 2019) due to the influence of warm Atlantic waters of the West Spitzbergen Current (Loeng, 1991; Saloranta, Haugan, 2001; Cottier *et al.*, 2005). Along the coast of Forland Sundet, strong longshore currents from SSE to NNW influence sedimentary depositional patterns and heat transport. The eastern shore is dominated by currents of the fjord system, which are directed from SE to NW (Torsvik *et al.*, 2019).

BEDROCK STRATIGRAPHY

Bedrock mainly consists of Carboniferous and Permian sedimentary rocks (Hjelle *et al.*, 1999) (fig. 3). The Billefjorden Group (Early Carboniferous) is represented by the Orustdalen Formation consisting of clastic terrestrial sediments which formed on vast denudative peneplains, alluvial fans and meandering rivers (Johannessen and Steel, 1992). The climate during the early Carboniferous was warm and humid, favoring the growth of biomass in high quantities, which eventually formed local coal horizons. This formation outcrops in the south-western tip of the study site and consists of sandstones and conglomerates of Tournaisian and Viséan age.

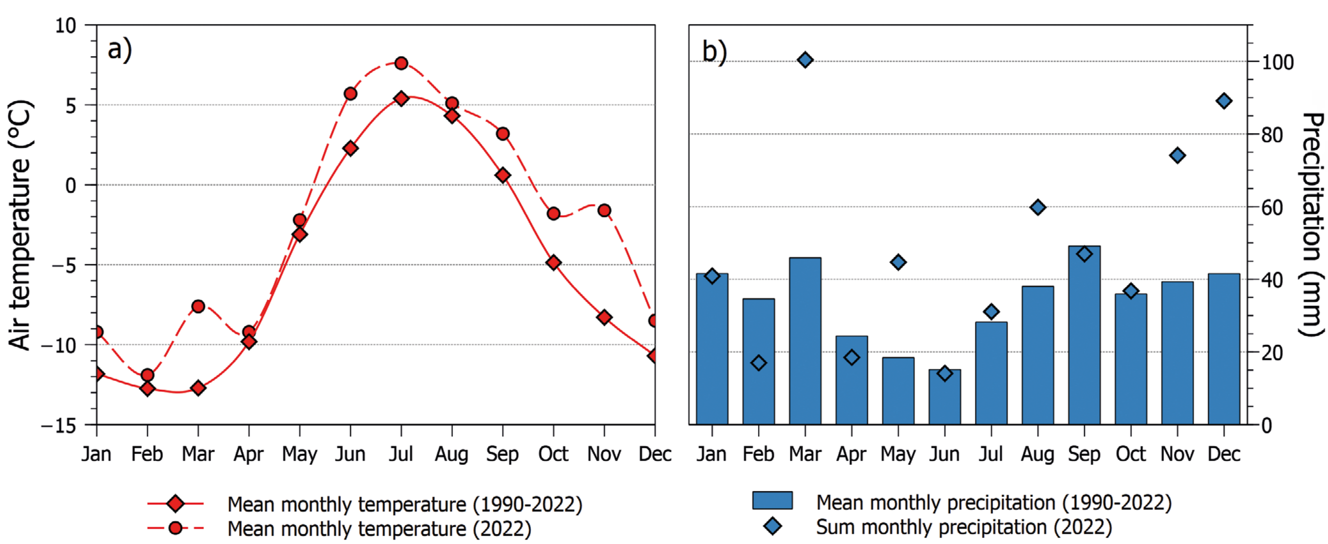

Figure 2 - Mean monthly values of a) air temperature and b) precipitation in Ny Ålesund (Meteorological data provided by Norwegian Centre for Climate Services).

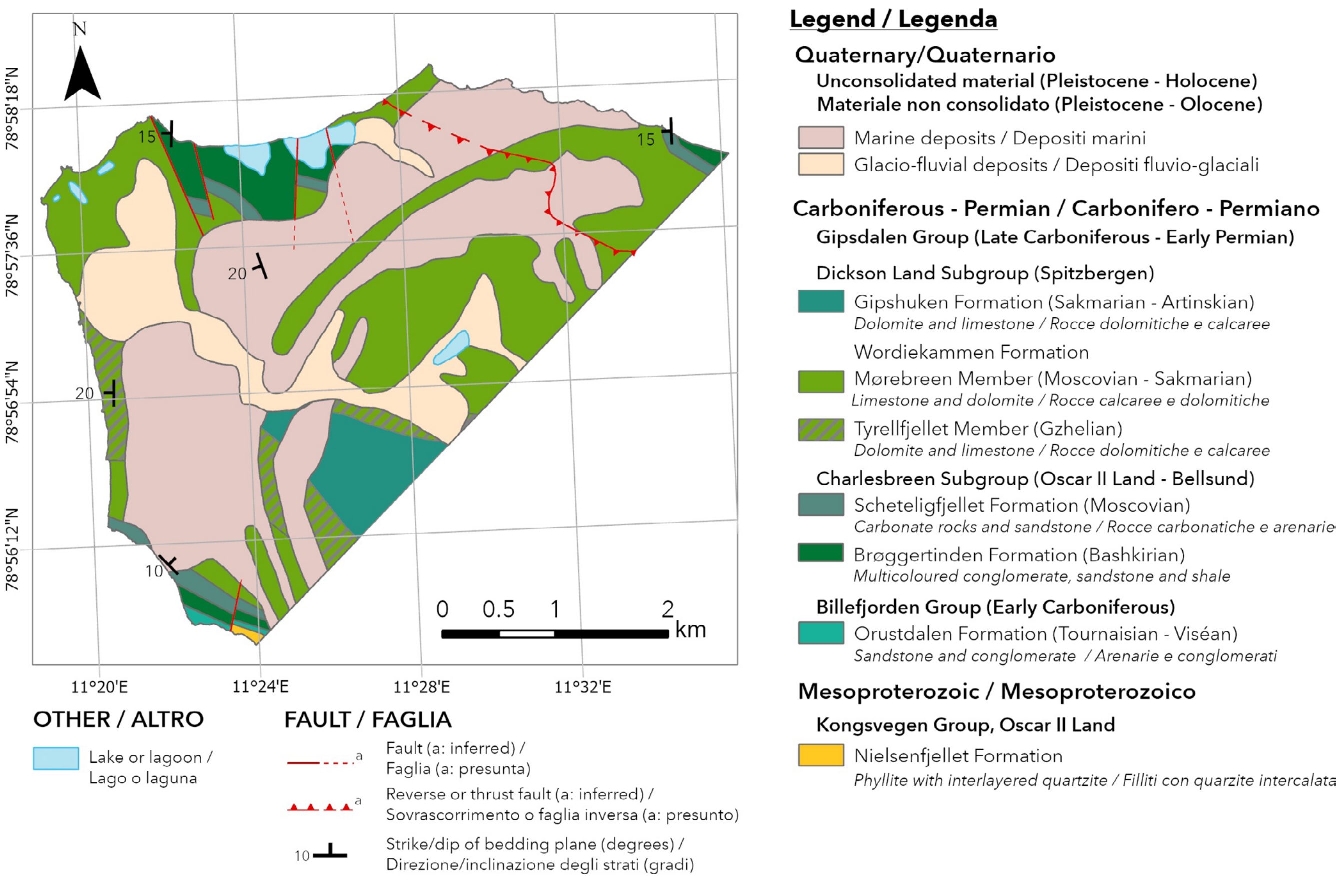

Figure 3 - Geological sketch map of Kvadehuksletta, modified after Hjelle *et al.* (1999).

After a marine transgression in the late Carboniferous, the Gipsdalen Group (Middle Carboniferous – Early Permian) developed and today it represents the majority of bedrock exposed on Kvadehuksletta. The lithostratigraphic units of the Gipsdalen Group represent the transition from a terrestrial into a shallow marine environment (Blomeier *et al.*, 2008). The Gipsdalen Group can be subdivided into two subgroups, the older Charlesbreen Subgroup and the relatively younger Dickson Land Subgroup. The Charlesbreen Subgroup is further differentiated between the Scheteligfjellet and Brøggertinden Formations.

The clastic sediments of the Brøggertinden Formation formed during the Bashkirian age and consist of multicolored conglomerates, sandstones, and shales (Thiedig *et al.*, 2001). Sediments of the Scheteligfjellet Formation (Moscovian) entail carbonate rocks and sandstones. Rocks of the Charlesbreen Subgroup are exposed locally in the south-western, north-eastern, and northern areas of the study site (fig. 3 and geomorphological map). They are overlain by the formations of the Dickson Land Subgroup.

The Wordiekammen formation is the most widely outcropping formation of the Dickson Land Subgroup and consists of two members, the stratigraphically lower Mørebreen Member (Kasimovian - Gzhelian) and the overlying Tyrellfjellet Member (Asselian - Sakmarian), which contains important detachment horizons in the context of the fold and thrust tectonics that characterize the SW of the Brøgger peninsula (Saalmann and Thiedig, 2001). Both formed under fully marine conditions (Blomeier *et al.*, 2008; Hanken and Nielsen, 2013) and consist of fossiliferous marine dolomites and limestones. The Gipshuken Formation represents the stratigraphically uppermost part of the Dickson Land Subgroup and can be found in the central part of the study area. The unit has been formed under marine shallow water conditions during the early Permian period of the Sakmarian and Artinskian age (Blomeier *et al.*, 2008).

Mesoproterozoic rocks are exposed in a small outcrop along the coastal cliff in the south-west of the study area. They belong to the Kongsvegen Group and display strata of the pre-Caledonian basement. The rocks are phyllitic with interlayered quarzitic schists and, locally, small granite dykes.

The structural framework of Kvadehuksletta is the result of seafloor spreading in the North Atlantic and Eurasian Basin during the Eocene. Kvadehuksletta lies in the vicinity of the West Spitzbergen Fold and Thrust Belt (WSFTB; Harland and Horsfield, 1974; Lyberis and Manby, 1993), a prominent intra-plate tectonic structure. Brøggerhalvøya represents the northernmost terrestrial unit of the WSFTB, which is 10-12 km wide in this area, and Kvadehuksletta is thus structurally affected by thrusting, which led to the formation of a frontal thrust belt (Gabrielsen *et al.*, 1992). The thrust belt prolongs towards the east into the Kongsfjorden (Bergh *et al.*, 2000; Saalmann and Thiedig, 2002).

MATERIAL AND METHODS

The geomorphological map was realised using photogeological interpretation techniques applied to high resolution remote sensing data. The image data were acquired during a joint campaign of the Alfred Wegener Institute of Marine and Polar Research (AWI) and the German Aerospace Center (DLR) in 2020 (fig. 4), using AWIs aircraft Polar-6 and the DLR Modular Aerial Camera System MACS (Lehmann *et al.*, 2011) in the MACS-Polar version. This camera system records images in the visible (VIS), near-infrared (NIR) and thermal-infrared (TIR) spectral ranges with ground sampling distances (GSD) ranging from 5 cm to 10 cm (VIS), from 10 cm to 15 cm (NIR) and 80 cm to 120 cm (TIR) with an along-track overlap > 80% in this campaign. The images were photogrammetrically processed at the DLR Institute of Optical Sensor Systems using aerial triangulation in combination with dense image matching. As final products a digital elevation model (DEM) as well as true orthophoto mosaics of the whole scene were derived with ground pixel sizes of 10 cm × 10 cm (RGB, NIR, DEM) and 45 cm × 45 cm (TIR). This dataset offers the highest resolution for any remote sensing dataset in this region. These data have been used to identify and analyse geomorphological units and landforms.

The structure and the legend of the geomorphological map follow the guidelines suggested by the Italian Geological Survey and by the Italian Association of Physical Geography and Geomorphology (Gruppo Nazionale Geografia Fisica e Geomorfologia CNR, 1986; Brancaccio *et al.*, 1994; Campobasso *et al.*, 2018). The symbols are in accordance with those adopted for other large-scale geomorphological maps in high mountain environments (Baroni and Carton, 1996; Panizza *et al.*, 2011; Carton *et al.*, 2021; Salvatore *et al.*, 2021) and for compiling small scale geomorphological and glaciological maps in polar region (Baroni *et al.*, 2004, 2005), with adaptations due to the detailed scale of the map and to the peculiar Arctic environment.

The various erosional and depositional landforms were depicted in different colours on the basis of their morphogenesis, while specific symbols indicated features, geometry, and nature. Morphodynamics constitute a key issue in the entire structure of the legend: according to Gruppo Nazionale Geografia Fisica e Geomorfologia (1986), active and inactive landscape features were represented respectively by darker and lighter tones of morphogenesis-specific

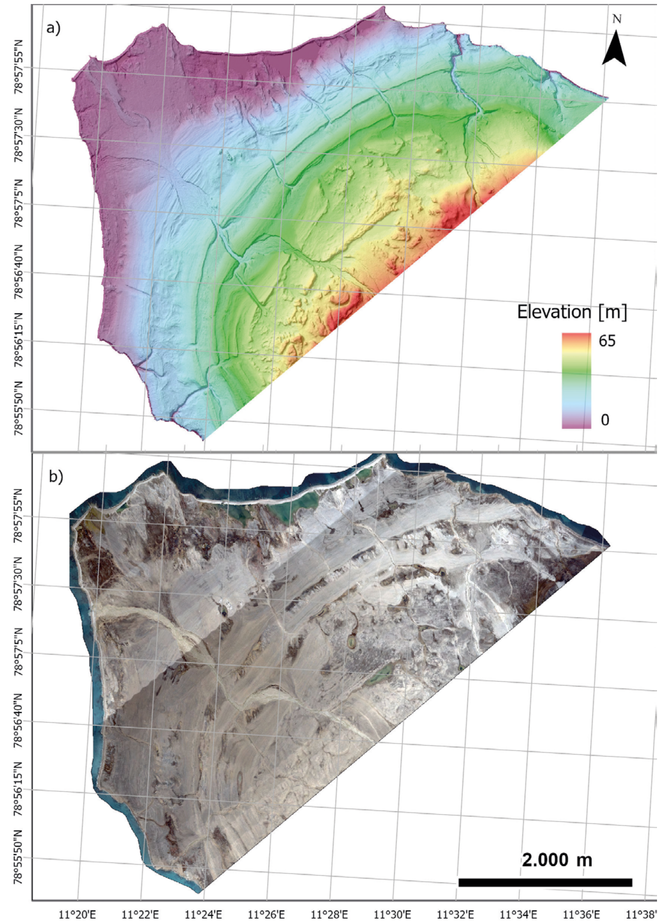

Figure 4 - Datasets used to map the study site of Kvadehuksletta. The study site was mapped using a Digital Elevation Model (DTM), with a pixel size of 10×10 cm (top) and an orthomosaic with a pixel size of 10×10 cm (bottom).

colour, considering active features resulting from of ongoing morphogenetic process driven by present-day morphoclimatic conditions.

The geomorphological data were manually digitised and acquired in the vector domain (*.shp, point, line, polygon according to their geometry) by using the ESRI software ArcGIS Pro 2.9.0. (coordinate system WGS84 UTM32N). Finally, the alphanumeric attribute tables (dBase, *.dbf) associated with vector files were populated by inserting data related to morphogenesis, morphotypes, morphodynamics and, when available, chronology.

Based on the DEM, parameters such as slope steepness, aspect and curvature datasets have been calculated and used for further landscape analysis. A surface model was generated, allowing to investigate the landscape in 2.5D, as well as producing anaglyphic digital terrain models for enhanced relief examination of the landscape to guarantee best remote sensing mapping results. Additionally, analogue stereoscopic images and photointerpretation techniques have been used for selected key sites.

THE GEOMORPHOLOGICAL MAP

The geomorphological map of Kvadehuksletta at the scale of 1:8000 is provided in the supplementary material. The detailed landscape analysis of the Kvadehuksletta peninsula allowed the characterisation of the spatio-temporal evolution of the area, which despite its monotonous appearance preserves a variety of landforms and deposits, due to coastal, fluvial, periglacial and gravitational processes.

The complex interplay of coastal processes has significantly shaped the landscape of Kvadehuksletta over time. A predominant characteristic of this landscape is the extensive coverage of coastal deposits, prominently manifested in the form of distinctive individual major berms, partially overlapping and locally organised into sequential arrangements of smaller berms, forming a coherent semi-circular pattern. Permafrost-shattered bedrock surfaces locally outcrop between berms, as the result of the erosive activity of marine highstands that initially abraded the carbonatic bedrock platform and secondarily shaped subaerially under the influence of intense frost shattering (after emersion). Amidst this deeply acting physical weathering, patches of relatively unaltered bedrock outcrops locally emerge. Kvadehuksletta showcases a diverse array of periglacial patterned ground formations, including distinctive sorted circles, stripes, intricate nets, and the characteristic polygons formed through thermal contraction cracking. Taken together, this environment stands as a complex range of landscape forming processes, offering valuable insights into the dynamic and multifaceted nature of polar coastal terrains which are further described below.

Hydrography

Present-day continental hydrography includes several elements such as lakes, lagoons, and streams. Small local glaciers (mainly cirque glaciers) are located on the hills about 4 km to the south-east of the study area (not included in the map), contribute with their meltwater to the hydrological cycle of the Kvadehuksletta. The study area retains an active fluvial drainage system, forming a variety of fluvial features reaching the sea or terminating into small lagoons. The main rivers are Kvadehukelva and Scheteligelva, about 6.3 and 4.1 km long, respectively. Kvadehukelva flows from SE to NW and terminates towards the Forland Sundet, forming a small, temporally submerged active river delta. The path of Kvadehukelva is crosscutting the post-LGM raised beach ridges nearly perpendicularly.

Scheteligelva crosscuts the strand flat from south to north and terminates into the outer Kongsfjorden. The upstream part of the river shows an evident braided channel pattern. The sides of the active riverbed are lined by inactive alluvial plains, where crevasse channels are detectable. These crevasse channels appear to be generally dry, but they are presumably reactivated during meltwater season, which induces high stands of the river. Towards the river mouth, Scheteligelva deeply crosscuts younger marine sedimentary units and forms a canyon-like river path with active fluvial erosional scarps, which can be up to 14 m high. The river path becomes narrower towards the river mouth and cuts into the surface exposing underlying bedrock (creating a canyon-like valley).

Next to Kvadehukelva and Scheteligelva, multiple smaller streams drain Kvadehuksletta. They typically emerge from local depressions, filled either permanently or seasonally with freshwater. The smaller depressions are situated on top of the marine sediments in between individual berms or in the areas between larger beach ridges.

Lakes are widespread and are typically located within topographic depressions situated between extensive beach ridges, or within minor berms. In some cases, these water bodies are connected by temporary or active streams, which are fed by glaciers, seasonal snow and permafrost melting waters. Most of the lakes have a shallow water depth (< 2 m), except for some of them having deeper water depths, situated in pre-LGM coastal sedimentary units (e.g., Groptjørna). Closed lagoons are located behind the present-day storm berm on the north-western shore of Kvadehuksletta (visible on the map), with inland beaches often featuring driftwood deposits. These lagoons often receive input from several smaller freshwater streams, which show tidal erosion scarps at the contact zone to the marine-influenced regions.

Surface and subsurface flow along water tracks is driven by seasonal freezing and thawing of the permafrost active layer. Individual subsurface water tracks can be identified on post-LGM beach ridges. The subsurface flow pathways convey snowmelt water and occasionally rainfall downslope, mostly in permafrost areas where water infiltration and circulation is restricted to shallow depths, and are well known from the high Arctic and Antarctic regions (Nicholson, 1979; Gooseff *et al.*, 2013; Paquette *et al.*, 2018). The tracks are marked by linear albedo changes in marine sediments, indicating increased water saturation and subsurface water flow through uncompacted sediments. The water tracks upper head is linked to permanent or seasonal standing bodies of water, from which they infiltrate into regions of lower elevation, sometimes sourcing local springs and small streams. When the active layer is not freezing, the subsurface water tracks facilitate the creation of springs along the boundary between permeable marine sediments and areas characterized by frost-shattered pavement, which becomes increasingly impermeable with depth.

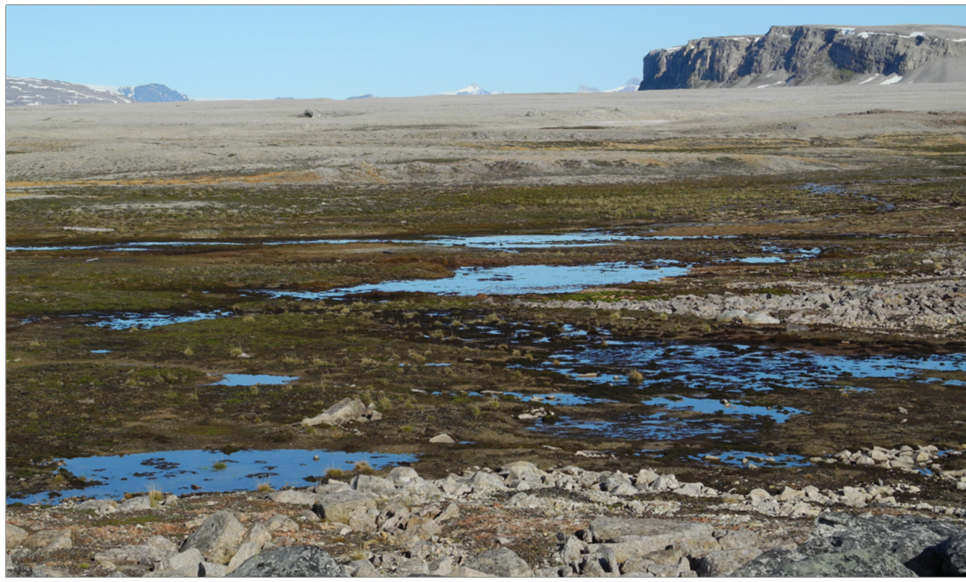

Figure 5 - Pond and swamp area in low lying areas close to the modern shoreline and lagoonal influenced regions (Photo by E. Hauber, 2023).

Lacustrine landforms and deposits

Lacustrine sediments have been deposited under the influence of past or seasonally active lacustrine conditions. They are characterised by higher soil moisture and tend to show higher vegetation coverage, leading to a lower surface albedo as well evidenced in remote sensing images. In places, where the vegetation is sparse, patterned hummocky terrain often forms in lacustrine sediments.

Ponds and swamps are hosted in internal areas characterised by limited drainage and moderate water inflow (fig. 5), and near-coastal areas where high vegetation rates and extremely wet soils are present. The excess water creates numerous, often interconnected, pond networks. Active streams are a constant freshwater source; however, these areas are also influenced by marine water input during highwater stands. Additionally, sites along the western coast might gain saltwater input due to ocean spray, which increase saltwater content of the soil in these areas.

Coastal landforms and deposits

The prominent landscape features of the area are coastal landforms and deposits, the shaping and evolution of which were strongly driven by eustatic and relative sea level changes induced by glacio-isostatic rebound affecting the northern Spitsbergen during the late Pleistocene and Holocene (Forman *et al.*, 1987, 2004; Brückner and Schellmann, 2003; Farnsworth *et al.*, 2020).

The analysis of photographic tone, texture and structure, and the degree of preservation of landforms, allowed us to recognise three main photogeological zones related to marine deposits, within which further units were distinguished.

The main marine deposit units correspond with the beaches chronosequence recognised and described by Forman and Miller (1984). Firstly, the pre-LGM marine deposits are evident in a morphologically dissected terrain above 43 m a.s.l. due to post-depositional influence of deglaciation, periglacial and fluvial processes. Secondly, marine sediments deposited after the LGM are generally better preserved and form sequences of contour-parallel beach deposits with prominent berms on their summits. Lastly, recent marine deposits shape the modern shoreline. The coastal landforms and deposits are described in detail below.

Pre-LGM marine deposits. The oldest marine deposits are present in the upper dissected terrain above 43 m a.s.l. (figs 6, 7). Measurements of $\delta^{13}C$ of whalebones collected in these deposits revealed ages older than 36,000 yr B.P. (Forman and Miller, 1984; Forman *et al.*, 1987), predating the LGM and possibly attributable to the Weichselian period. The marine sediments belonging to these units are heavily affected by surface weathering processes and periglacial reworking, but experienced glacio-tectonic deformation during the LGM, as testified by several erratics distributed on these deposits (Henriksen *et al.*, 2014).

The erosional features found on pre-LGM marine sediments display clear differences between the north-eastern and south-western regions. Landscape analysis indicates that the north-eastern region has undergone substantial erosion, evident in a dissected and smoothened relief masking the primary morphology of berm-topped coastal sediments, likely caused by the fast-flowing extensive ice of the Kongsfjorden during the late Weichselian (Henriksen *et al.*, 2014b). In contrast, the south-western region shows lesser degrees of erosion, suggesting the presence of slower-moving glacier flow with minimal erosional force (Landvik *et al.*, 2003; Alexanderson *et al.*, 2011). The surface covered by pre-LGM marine deposits is dissected by an irregular channel network, which forms isolated 1-2 m high ridges in

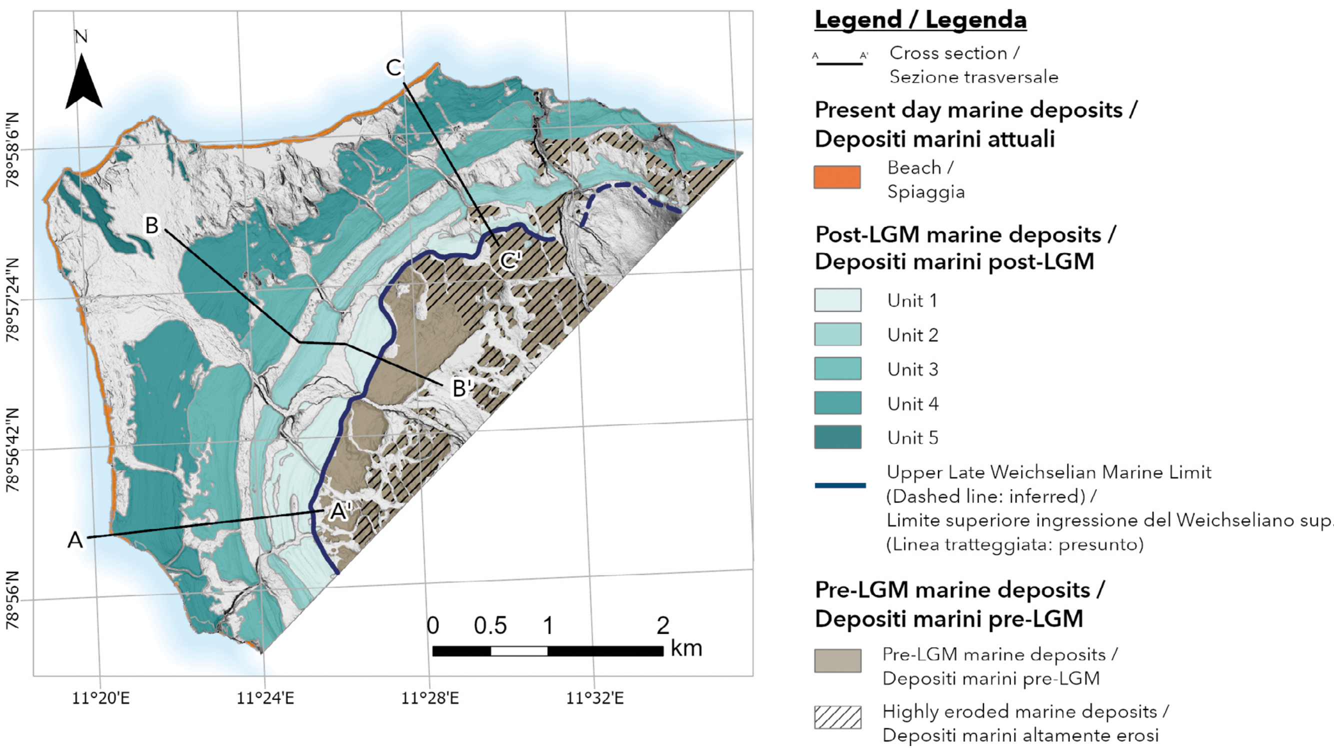

Figure 6 - Morphochronologic overview of marine deposits and their subunits at Kvadehuksletta, including possible marine limits during the Late Weichselian (hillshade from DEM processed by DLR, 2020).

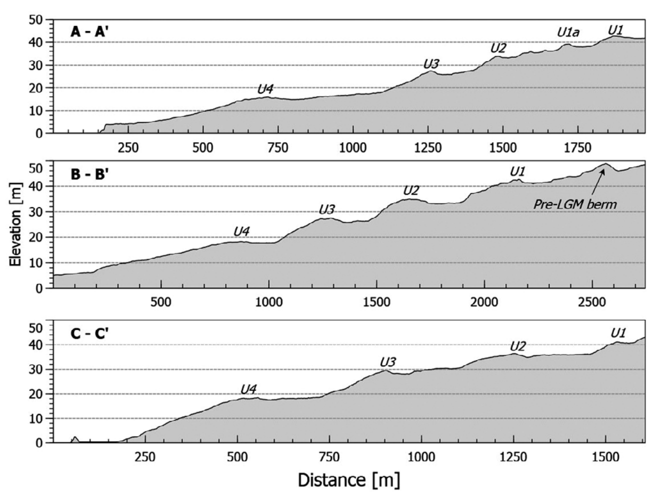

Figure 7 - Cross sections along beach transects (see Fig. 6 for location).

between channels. The channels of this network follow the direction of major tectonic features of the WSFTB from NNW to SSE, which control the orientation of the channel network. Although the surface of this sedimentary unit is in large parts highly eroded, individual, faint coherent crests of berms can be detected in the south-western part, which culminate at 48 m a.s.l.

The pre-LGM sediments and unit U1 limit (fig. 6) depict the upper Late Weichselian marine limit.

Table 1 - Highest crest elevation of marine morphochronological units at Kvadehuksletta.

Subunit	Berm crest elevation along transect [m]		
	A -A'	B – B'	C – C'
Pre-LGM	-	48.1	-
U1	41.0	42.3	42.6
U1a	39.1	-	-
U2	36.3	34.7	33.7
U3	29.1	27.1	27.3
U4	18.0	18.2	15.8
	Highest crest elevation [m]		
U5	5.7		

Post LGM marine deposits. The majority of the study site is mantled by Late Weichselian and Holocene marine deposits, which can be differentiated on the basis of their morphometry (crest elevation). A total of five remarkably well-preserved paleo-beach units were identified (table 1), which cover 8.9 km² of the study site. Four of them (U1-U4) form arcuate and parallel ridges at the strand flat, while one separated cluster (U5) exists in a perpendicular alignment at the spit of Kvadehuken (fig. 6). The units of the prominent paleo-beaches are well separated along the middle (NW-SE) axis of the peninsula. Towards the NE and SW shorelines of the Kongsfjorden and Forlandsundet, beach units tend to overlap each other (Miller *et al.*, 1989).

All the units show individual smaller berms, well detectable by the MACS elevation model, having heights of 0.2-0.5 m. The crests of the largest berms are situated on the hinterland proximal side of each individual sequence (fig. 7). The smaller, superimposed berms generally follow the pattern of the major sequence but can locally deviate as proximate subsurface features like internal structures of shallow bedrock or bedrock outcrops disturbed this general pattern during the time of their formation.

According to Forman *et al.* (1987) and Miller *et al.* (1989), Unit 1 developed during the Late Weichselian period, shortly after the LGM during the beginning of the isostatic rebound of the Brøggerhalvøya. This unit has a maximum berm elevation of 45 m (table 1). Individual berms tend to show higher degree of erosion than the relatively younger beach units U2-U5 at lower elevations but are still well detectable in most cases. In contrast to unit U2-U5, the arcuate deposition pattern of the beach unit is interrupted northwest of the lake Groptjørna. Unit U2 forms about a 260 m wide uninterrupted marine deposit. The highest berm reaches an elevation of about 36.3 m in the western sector, while the hight of the crest is reduced toward the east by 2.6 m and peaks at 33.7 m (table 1). Units U3 and U4 define sub-parallel ridges at lower elevations. Unit U3 is 350 m wide and culminates at 29.1 m asl along the western profile and only 27.3 m a.s.l. at the eastern profile (fig. 6), and therefore a general height difference towards the east of 1.8 m can be observed.

Unit U4 is the youngest unit on Kvadehuksletta and overlaps the relatively older unit U3. The crest top is less steeply defined than at the other units and culminates at 18 m. Lakes and lacustrine sediments rest on local depressions at the contact zone between units U3 and U4.

Unit U5 is forming an isolated cluster in the north-western part of the modern low land of the strand flat at Kvadehuken. The marine sediments of this unit are superimposing frost shattered bedrock. Their alignment is directed from an NNW to SSE direction and seems to follow the dipping of the underlying bedrock. Unit U5 is the lowest beach unit with a maximum crest height of 6.6 m. In parts, well developed berms can be detected, defining the surface topography of the beach unit. This unit is particularly prone to be covered by surface vegetation, probably due to the exposure to ocean spray during storm events as well as excess water from surface flow and accumulation in nearby depressions of the surrounding low-land (Wojcik *et al.*, 2019).

Inactive wave-cut platforms are widespread in all the study area and outcrop at different elevations. After the LGM the platforms progressively emerged being deeply affected by frost action (fig. 8a).

Small dendritic tidal channels with small catchments can be observed at the inner border of present-day lagoons located on the Kvadehuken spit and in other low-lying areas along the shoreline. The channels can reach hundreds of metres in length, few tens of metres in width and about 1 m in depth. They act as temporary drainage pathways for waves during storm surges and high tides and drainage pathways of surface meltwater during spring. Along the upper shore of the lagoon, numerous trunks of driftwood demarcate the levels of minimum water high stands at 1.5 m during high water-energy conditions.

Active marine landforms and deposits. The modern coastline of Kvadehuksletta is morphologically different with respect to older and higher post-LGM berm units. The western and north-eastern shoreline forms steep cliffs, with active marine erosional scarps (fig. 8b). The eastern cliff along the Kongsfjorden is up to 25 m high, while the edge of the cliff at the Forlandsundet reaches heights of 15 m a.s.l. Along the cliff, strata of underlying bedrock are vertically exposed and are topped by 5 m of unconsolidated massive marine deposits. This layering causes differences in slope steepness along the cross section of the cliff: the lower cliff section is nearly vertical, while the slope of the upper part is characterised by gentler slope inclinations due to lithologies with different erodibility. At the cliff foot, modern marine beach deposits accumulate locally between bedrock headlands, forming isolated berms up to 2 m height. Wave-cut platforms locally border the present-day shoreline and develop at the base of cliffs in the south-western sector of the area.

Towards the north, the modern coastline changes from a cliff-dominated into a barrier beach-dominated coastline. Exceptions are local protruding outcrops of shallow bedrock. Also, in spit-proximal areas wave cut platforms have been formed. In between the spits, beach segments developed, forming a 30 m wide beach unit of a single major berm up to 2.5 m height. A prominent feature of the northern coast are the Hukbogen-lagoons (Vestrehuk-, Midtrehuk- and Austrehuk *Lagoona*) which are enclosed by the berm structure. Sediment sources of modern beach material originate from bedrock along the cliff site and from fluvially transported sediments during the meltwater season. Fluvial sediment is trapped in the basin of the lagoons if it is transported by lagoonal-terminating rivers and contributes to the build-up of smaller intra-lagoonal beach segments (Klemsdal, 1986).

Fluvial and fluvioglacial landforms and deposits

Kvadehuksletta retains an active fluvial drainage system, forming a variety of fluvial features and locally small temporally submerged active river deltas (i.e., Forland Sundet). The main rivers crosscut the post-LGM raised beaches nearly perpendicularly, as well as older beach deposits and fluvioglacial fans. Fluvial erosion formed distinct erosional scarps up to 4 m in heigh, which locally are markedly convergent (fig. 9a), originating in places canyon-like trenches that can expose the underlying bedrock (fig. 9b).

Inactive alluvial fans are present throughout the area, in particular widely above 25 m in elevation. They mainly cover the oldest marine abrasion platforms and are deeply incised by active streams. The oldest alluvial fans, which have been formed following the deglaciation after the LGM, subsequent eustatic marine rise and isostatic uplift of deglaciated areas, developed between marine berms deposited in response to relative sea level changes.

The main active alluvial fans develop below 20 m in elevation, although some smaller in size are present at higher elevations. Noteworthy is the extensive fluvial flow-dominated fan with a network of braided channels fed by the Kvadehukelva in the north-western sector, which covers the post-LGM marine deposits (unit U4) and abrasion platforms.

The pre-LGM marine sediments preserve a secondary inactive river network, in which only seasonal meltwater discharge accumulates (fig. 9c). In contrast to modern streams, the flow direction is from south-west to north-east. The complex pattern might have been predefined during glacial coverage and subglacial meltwater transport or be related to internal structures of the underlying carbonate bedrock or a combination thereof.

Periglacial and nival landforms

Periglacial landform types are diverse and very common in Kvadehuksletta. Most of the landscape shows signs of surficial periglacial reworking and nival processes, including very well-developed patterned ground features, as well as landforms originated by frost shattering.

Six different categories of patterned ground can be detected in Kvadehuksletta. They include polygonal patterned ground, sorted circles and related features (e.g., sorted circles s.s., elongated sorted circles, patterned hummocky terrain), sorted nets and soil stripes (figs 10, 11).

Networks of polygonal patterned ground appear mostly on top of local ridges of pre-Late Weichselian marine sediments, which have not undergone fluvial reworking (figs 10a, 11a).

In general, the networks developing on pre-LGM marine deposits tend to form high-centred polygons with trough depths of 20 cm and are integrated into well-connected polygonal networks.

On flat areas, networks present larger primary cracks, from which secondary cracks intersect the polygon network geometry. On ridges, isolated and less well-connected polygon-nets can be observed.

On post-LGM beach units U1 and U2, polygonal patterned ground, which can be locally observed also on the crests, does not form closed polygons but by hexagonally interconnected troughs. A faint network can be also recognized on an inactive alluvial fan of Kvadehukelva, which has been deposited between post-LGM beach units U1 and U2. Individual polygon size varies, but usually polygons have diameters of 15-40 m.

The sorted circles on Kvadehuksletta are among the best-developed examples worldwide (fig. 10b). They are abundant on nearly all the surfaces, with the exception of the most active riverbeds. They form undisturbed circles on the top of post-LGM beach ridges and have diameters ranging from 1 m to 10 m. On steeper slopes, they evolve into elongated patterns (fig. 10c), with long axes parallel to the steepest slope gradient. Their width is similar to the diameter of circles in flat areas, but their length is driven by the slope length and steepness.

Sorted nets are related to circles and elongated circles in their origin but tend to form open networks (Washburn, 1956). They originate in water-saturated soils and can be found in areas of frost-shattered pavement as well as in pre-LGM beach sediments (fig. 10d).

Sorted stripes exhibit a distinctive pattern where parallel lines of stones are aligned with strips of predominantly finer material, following the steepest slope (Washburn, 1956). Sorted stripes are particularly widespread and well-preserved in the north-eastern part of the study site, where they extend over the whole slope reaching maximum lengths of 400 m (fig. 10e).

Often different forms of patterned ground exist in combination or smoothly transition into each other in Kvadehuksletta (fig. 11b, c).

Frost shattered limestone pavements are widespread in all the mapped area and are primarily defined as deeply frost shattered bedrock area. They develop on flat surfaces which initially underwent marine erosion due to wave activity as wave-cut platform. The continuous exposure to intense frost shattering after the isostatic uplift, resulted in further secondary geomorphological processes, constructing deeply frost shattered surfaces, dominating the areas, which are not covered by marine sediments.

In sedimentary deposits, close to the modern cliff line several *dellen* have formed (fig. 9d). These U-shaped small valleys are about 50 cm deep and can be several metres wide. They have a small catchment and serve as drainage pathways during the snowmelt season.

Glacial landforms and deposits

In the Kvadehuksletta area, erratic boulders of different lithology are abundant and rest on pre-LGM coastal marine sediments (fig. 12a) and on relict coastal erosion platforms. In the geomorphological map, boulders with diameters larger than 1 m are mapped.

The channel network observed in pre-LGM marine deposits above 43 m a.s.l. diverges from the flow direction of modern riverbeds and can possibly be interpreted as a remnant of relict subglacial meltwater activity. Although an overall alignment to a N-NE direction can be observed, the network pattern is complex with many interconnecting channels. According to Landvik *et al.* (2003) who de-

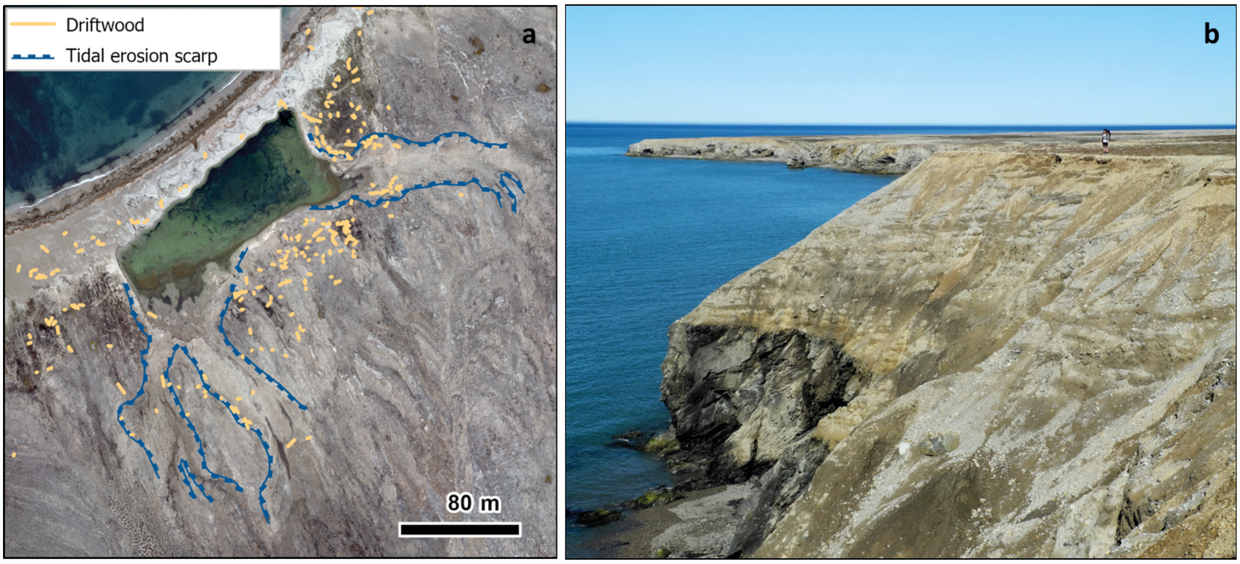

Figure 8 - a) Lagoon at Kvadehuken with small paleo-tidal channels which developed during higher relative sea levels. These channels act at present as local drainage pathways of excess surface waters. Washed up driftwood is visible and evident for recent flooding during storm events (orthophoto by DLR, 2020). b) Modern 20 m high cliffside along the western shoreline of Forlandsundet. Visible are layered coastal marine sediments, which superimpose bedrock cliffs south of Kulmodden. Human for scale on top right (photo by E. Hauber, 2022).

Figure 9 - a) Kvadehukelva stream crosscutting coastal sedimentary units, showing the characteristic braided pattern. b) Steep-walled river flank carved in bedrock unit. c) Paleo-channel of the secondary river system in pre-LGM marine sediments. d) Trough-shaped small valley (*delle*), about 50 cm deep and up to several meters wide. They formed by snow action and meltwater discharge in catchments close to the modern cliffs (photos by E. Hauber 2022).

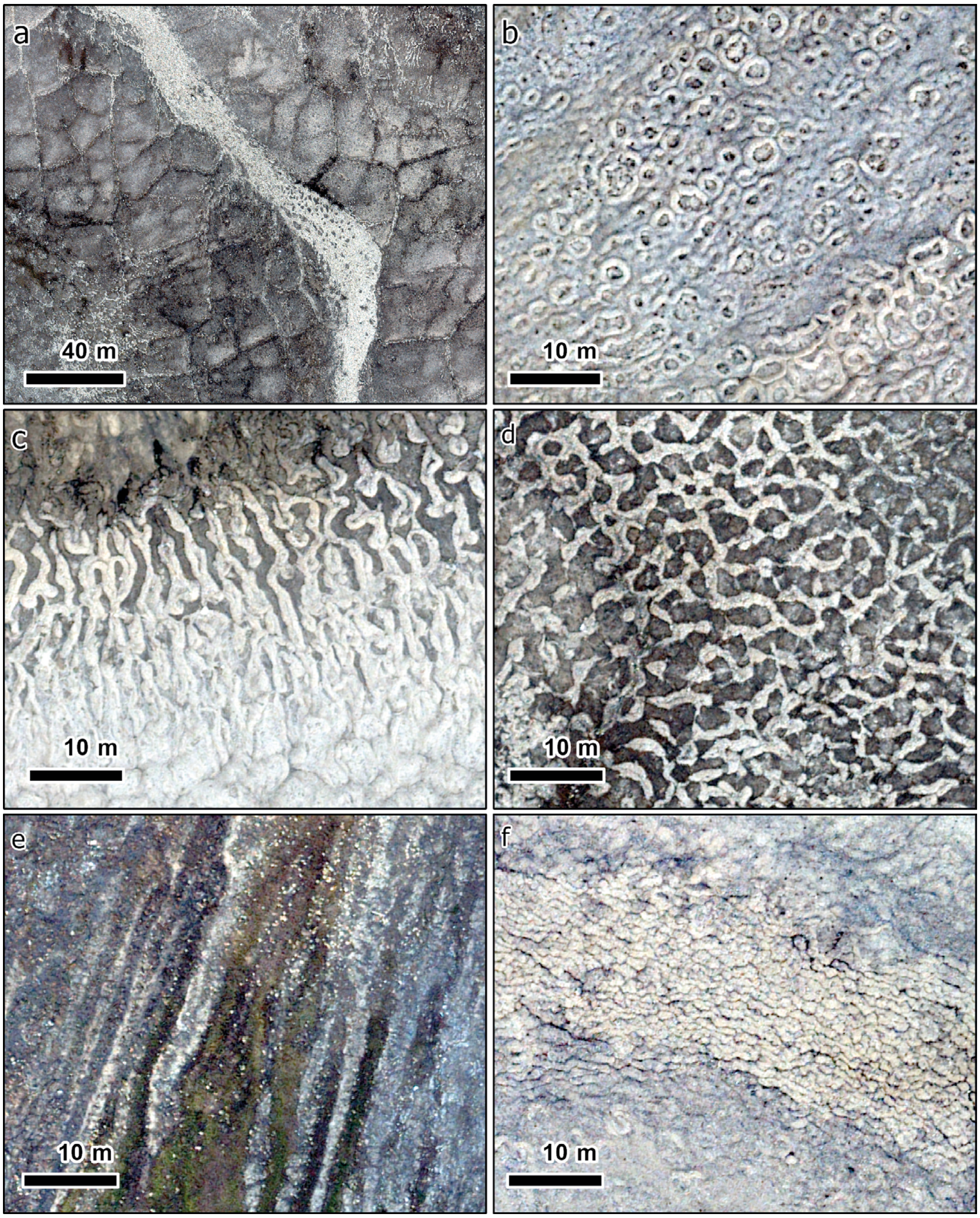

Figure 10 - Categorization of patterned ground in Kvadehuksletta. a) Network of thermal-contraction polygons. b) Well developed sorted stone circles on top of Holocene raised beach. c) Elongated sorted stone circles on slope of Holocene raised beach. d) Sorted nets. e) Sorted stripes. f) Patterned hummocky terrain in semi-active fluvial deposits (orthophotos: DLR, 2020).

scribed similar environments on the north-western part of Svalbard, this pattern might have been initially formed during previous glaciations.

Gravity-induced landforms and deposits

Although the study area has a very low relief energy, landforms and deposits due to gravity driven mass wasting are evident at the toe of the marine cliffs and in few areas further inland. Among these, a 2 m high inland cliff has been observed at the boundary between the lagoonal influenced area and the marine beach deposits. The cliff's degradational edge is at 14 m above sea level and drops by 2 m (figs 12 c, d). A scree slope consisting of finer weathered material develops at the cliff toe.

Bedrock Features

Bedrock outcrops form small local remnant features due to selective erosion of mainly limestone and dolomite of Permo-Carbouniferous formations (see the Stratigraphy and Lithology insert on the geomorphological map). Elongated patches of bedrock locally protrude through units of marine sediments, following the dipping of the strata. A bedrock outcrop to the east of Kvadehukelva is protruding the surrounding landscape by 6 m (fig. 12b). The surface does show signs of frost shattering, but to a significantly less degree than the previously described frost shattered pavement. Instead, the surface is highly affected by microkarstic erosion, forming karren rock surfaces. Locally smaller peaks of bedrock outcrops can be detected, which

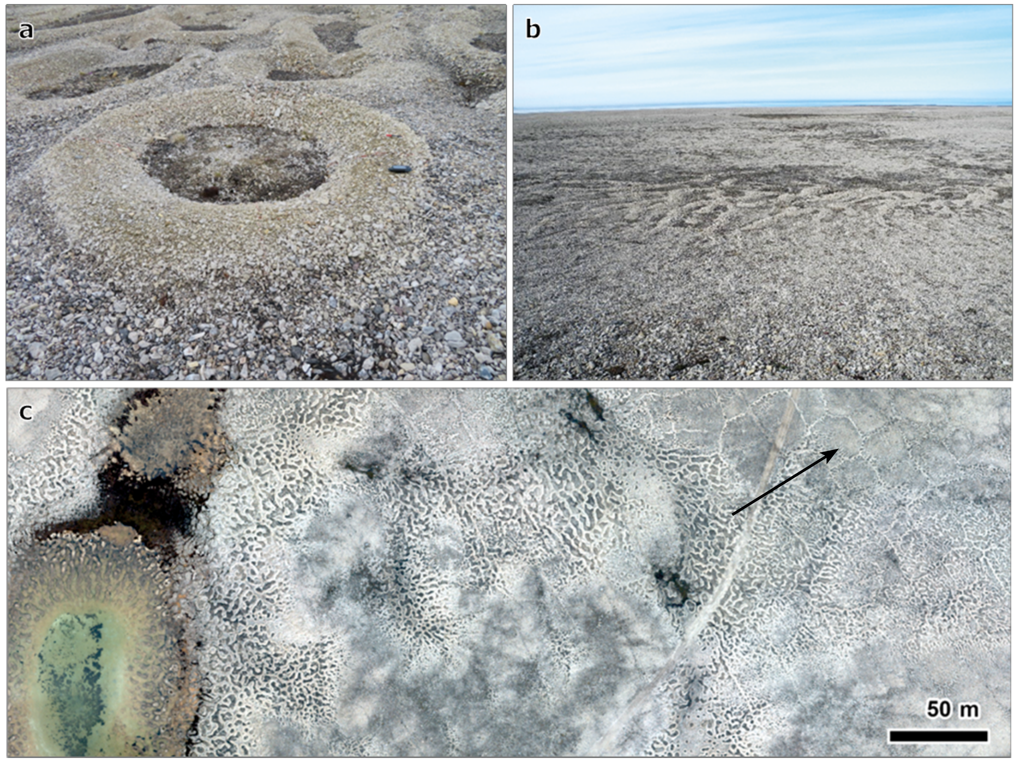

Figure 11 - a) Example of a well-developed circle (in the foreground), and elongated circles (in the background; GPS device for scale; photo by H. Hiesinger, 2019). b) Transition of elongated circles into nets (photo by E. Hauber 2022). c) Transition and interconnectivity of different patterned ground populations in pre-LGM marine deposits. The arrow indicates a a network of thermal-contraction polygons, on which sorted nets have formed. Noticeable is also the deep pond in the SW into which the sorted net prolongates into. A faint gravel track for scale runs from north to south in the eastern part of the image (orthophoto: DLR, 2020).

protrude through marine sedimentary units, usually less than 10 m wide, which can be interpreted as tor-like features.

Other features

Other features of anthropic origin are also present in the study area. Sediments on top of the crest of Unit 3 have been levelled in the 1960s for the planned construction of an airstrip. In between the airstrip and Groptjørna, the Geopol Hut was established. Several levelled dirt roads exist, which connect Geopol and the airstrip with the coast, and unlevelled roads connect Ny Ålesund with Kvadehuksletta. At Kongsfjordneset, the ruins of former huts can be found. At Kvadehuken a position light, a permafrost borehole and a meteorological station were installed.

DISCUSSION AND CONCLUSION

This paper presents the geomorphological map of Kvadehuksletta at the scale of 1:8000, realised adopting for the first time in these areas criteria for cartographic representation and legends that consider morphogenesis, morphotype and morphodynamics. Kvadehuksletta is an impressive example of a post-LGM raised strand flat in the high Arctic and displays a complex assemblage of landforms and deposits due to processes of different origin, which shaped the area during and after the LGM. The complex geomorphological assemblage of fluvial, marine, lacustrine, periglacial, glacial, and mass wasting landforms as well as present-day hydrologic features derives from complex relationships of different processes and changing dynamics on high arctic coastal environment.

The Kvadehuksletta peninsula landscape assemblages, below the glaciated area, include sectors characterised by different ages of the landforms and deposits. The upper pre-LGM coastal sediments are characterised by evidence of intense glacial and periglacial activity. This upper dissected pre-LGM deposits have been significantly eroded by cycles of Pleistocene glaciation and conditioned by the isostatic response of the Svalbard area. The dissected terrain represents an area which underwent erosion during multiple glacial events. In these sediments a distinctive, semi-chaotic drainage pattern developed, which may have been shaped during times of extensive glaciations and resulting basal meltwater flow. The original surface of these sediments is preserved on top of residual local hills. In contrast to younger sedimentary units, no small-scale coastal geomorphological features like berms can be observed on the deposits. Marine sediments situated between 42 m and 49 m a.s.l. have been estimated to an age of 60-160 ka and originated during ice-free conditions on the peninsula, tentatively correlated to the Eemian (MIS 5e; Forman and Miller, 1984; Forman *et al.*, 1987; Miller *et al.*, 1989). A prominent boundary is visible between the pre-LGM marine sediments and sediments which have

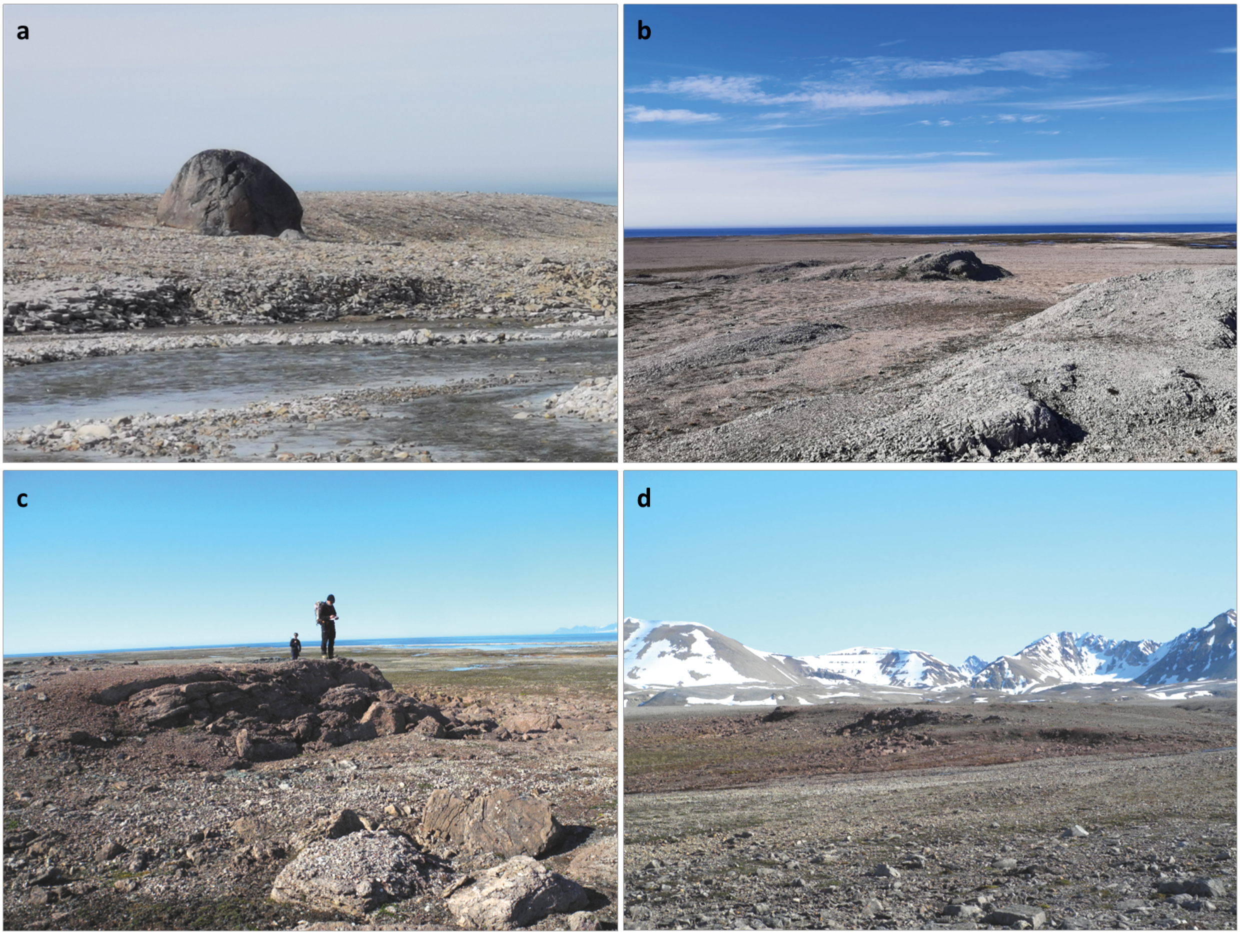

Figure 12 - a) 2.6 m high erratic boulder on pre-LGM marine sediments at 44 m a.s.l. located close to the river bench of Kvadehukelva, which eroded marine sedimentary units and underlying bedrock (carbonatic rocks of the Wordiekammen Formation). b) Limestone and dolomite bedrock to the east of Kvadehukelva situated at 18 m a.s.l. emerging from marine sediments (photos by A. Johnsson, 2022). c, d) 2 m high degradational cliff, consisting of multicoloured conglomerates of the early Carboniferous Brøggertinden formation.

been deposited as a consequence of isostatic uplift and eustatic sea-level change after the LGM (figs 4b and 6). This boundary is referred to the Late Weichselian Marine Limit and has been dated at other localities in western Spitsbergen to ≤12 ka BP (Salvigsen and Nydal, 1981; Salvigsen and Osterholm, 1982). The genesis of pre-LGM sedimentary marine deposits can be subdivided into two stages: pre-Weichselian and pre-LGM marine deposits (fig. 6).

Sequence of post-LGM raised beaches below 42 m a.s.l. are characterised by well preserved examples of marine beach deposits, which formed during stillstands or, eventually, smaller transgressions during an otherwise continuous relative sea level rise accompanied by isostatic uplift after deglaciation (Forman and Miller, 1984; Forman *et al.*, 2004). The underlying bedrock underwent intense marine erosion, leading to the development of well-defined abrasion platform. Due to prolongated exposure to freeze-thaw cycles, these platforms were widespread affected by deep frost shattered pavements.

The modern lowland, close to the coast, includes lagoons, active alluvial fans, and inactive abrasion platforms exposing strongly weathered bedrock in the north-western part of the area. The present-day coastline is very articulated, alternating sectors dominated by rocky cliffs up to 20 m a.s.l. (at the foot of which can develop storm beaches), and sectors where storm barrier beaches prevail, which locally delimit lagoon areas. The latter are more prevalent in the northern sector, while the former are more evident in the western sector where cliffs are frequently connected to abrasion platform.

The marine sedimentary deposits are incised by river fed by glacial meltwater and/or by snowmelt and seasonal melting of permafrost.

Most surfaces in Kvadehuksletta show periglacial reworking, forming a variety of patterned ground features, including some of the best examples of sorted frost circles worldwide (fig. 8). This inventory of patterned ground features offers opportunities beyond terrestrial geosciences. The Martian surface is known to display a variety of patterned ground (e.g., Mangold, 2005; Ulrich *et al.*, 2012). To understand planetary surface features, comparisons to terrestrial analogues can be extremely useful (Baker, 2014). Specifically, it has been shown that the landform assemblages on Svalbard are very useful as morphological analogues for Martian cold-climate landforms (Hauber *et al.*, 2011; Buer *et al.*, 2019). Geomorphological maps like the one presented in this study depict patterned ground with information of their contextual setting at very high spatial detail. Therefore, they are valuable tools to construct working hypotheses for the origin of morphologically similar landforms on Mars and develop testable predictions that help to verify or reject such hypotheses.

As elsewhere on Svalbard (e.g., Gilbert *et al.*, 2019; Kasprzak, 2020; Tavakoli *et al.*, 2021; Bazin *et al.*, 2021; Rotem *et al.*, 2023), Kvadehuksletta is a noteworthy study site for cryopeg detection and analysis. Cryopegs are enclosed and isolated pockets of briny liquid water in the otherwise frozen permafrost soil (Gilichinsky *et al.*, 2003). The combination of layered sediments and their aquiferic and aquicludic potential, which underwent top-down freezing, potentially favours the development of cryopegs in Kvadehuksletta. These cryopegs are especially well suitable for analogous research, as they have formed in a setting, where their location can be unambiguously correlated with observable geomorphological features. At Kvadehuksletta multiple sites could have favoured the development of cryopegs after previously submerged saline sediments were raised above sea level, followed by permafrost formation which may have redistributed salts downwards. From studies in Alaska it is known that cryopegs form in drained, inactive fluvial sediments (Stephani *et al.*, 2020) which is the case for multiple sites in the study area. In particular, where drained fluvial sediments underwent up down freezing after the Kvadehukselva river changed its course towards the north-west (centerpoint: 78° 57' 09.1'' N, 11° 26' 14.6'' E). Furthermore cryopeg development is in particular favoured if sediments have been influenced by the presence of saltwater during or after their genesis (Iwahana *et al.*, 2021). This applies for all coastal sediments but specifically the internal layering and overlapping of two main berm units which centres at 78° 58' 01.8'' N, 11° 28' 11.3'' E. Also, areas which get periodical saltwater income due to ocean spray are favourable places for cryopeg development, which is mainly the case for localities close to the modern western coastline, as seen by coast parallel increase of vegetation.

Kvadehuksletta is an extraordinary study site for correlating a variety of single processes to specific geomorphological features, enabling to get insights in their spatial and temporal development under dynamic conditions in a polar desert.

SUPPLEMENTARY MATERIAL

The geomorphological map associated to this article can be found in the online version at https://doi.org/10.4454/23dce671.

AUTHOR CONTRIBUTION

This study was developed with contributions from all authors: CB conceives the work; CB, MCS, CVS carried out the interpretation of remote sensed data and realised the geomorphological map; CVS and EH performed field checks; TB realized the orthophoto and the DEM of the investigated area; CB, MCS and CVS wrote the manuscript with contribution from EH. All the Authors equally contributed to the final version of the manuscript. The project was directed and coordinated by CB, MCS and EH.

ACKNOWLEDGEMENTS

This research was conducted in the framework of the ì) PhD Course in Earth Science 36th Cycle at the University of Pisa, ìì) the CNR Program GEOPATTERNS 2022-23 - *Landscape analysis and deglaciation patterns (Ny Alesund, Svalbard)*. E.H. was supported in the framework of the High Resolution Stereo Camera project at the German Aerospace Center (DLR). C.S. fieldwork during the KOP132 expedition to Kvadehuksletta (2022) was supported by a PhD travel grant from the FAZIT-STIFTUNG. The expedition logistics has been supported by the French-German Arctic Research Base AWIPEV. We would like to thank the AWIPEV staff for the logistical support during the fieldwork in Ny Ålesund. We also thank Prof. Dr. Harald Hiesinger and Dr. Nico Schmedemann (University of Münster) and Dr. Andreas Johnsson (University of Gothenburg) for their helpful suggestions and comments during the KOP132 expedition to Kvadehuksletta in 2022, and Dr. Michael Angelopoulos (AWI) for discussions on cryopegs. Jörg Brauchle (DLR) helped with the acquisition of the MACS data, and Matthias Geßner (DLR) supported the data processing.

REFERENCES

Alexanderson H., Landvik J.Y., Ryen H.T., 2011. *Chronology and styles of glaciation in an inter-fjord setting, northwestern Svalbard*. Boreas, 40 (1), 175-197. https://doi.org/10.1111/j.1502-3885.2010.00175.x

Baker V.R., 2014. *Terrestrial analogs, planetary geology, and the nature of geological reasoning*. Planetary and Space Science, 95, 5-10. https://doi.org/10.1016/j.pss.2012.10.008

Baroni C., Carton A., 1996. *Geomorphology of the upper Val di Genova (Adamello Group, Central Alps [Geomorfologia dell'Alta Val di Genova (Gruppo dell'Adamello, Alpi Centrali]*. Geografica Fisica e Dinamica Quaternaria, 19, 3-17.

Baroni C., Frezzotti M., Salvatore M.C., Meneghel M., Tabacco I.E., Vittuari L., Bondesan A., Biasini A., Cimbelli A., Orombelli G., 2004. *Antarctic geomorphological and glaciological 1 : 250,000 map series: Mount Murchison quadrangle, northern Victoria Land. Explanatory notes*. Annals of Glaciology, 39, 256-264.

Baroni C., Biasini A., Bondesan A., Denton G.H., Frezzotti M., Grigioni P., Meneghel, M., Orombelli G., Salvatore M.C., Della Vedova A.M., Vittuari L., 2005. *Mount Melbourne Quadrangle, Victoria Land, Antarctica 1:250,000 (Antarctic Geomorphological and Glaciological Map Series).* Fluctuations of Glaciers 1997-910X, VIII, 38-40.

Bazin S., Syed S.G., Gilbert G.L., Etzelmüller B., 2021. *Capacitive Electrical Resistivity: An Alternative Non-Invasive Method for Permafrost Monitoring.* NSG2021 27th European Meeting of Environmental and Engineering Geophysics, 1-5. https://doi.org/10.3997/2214-4609.202120013

Bergh S.G., Maher H.D., Braathen A., 2000. *Tertiary divergent thrust directions from partitioned transpression, Broggerhalvoya, Spitsbergen.* Norsk Geologisk Tidsskrift, 80 (2), 63-81. https://doi.org/10.1080/002919600750042573

Berthling I., Berti C., Mancinelli V., Stendardi L., Piacentini T., Miccadei E., 2020. *Analysis of the paraglacial landscape in the Ny-Ålesund area and Blomstrandøya (Kongsfjorden, Svalbard, Norway).* Journal of Maps, 16 (2), 818-833. https://doi.org/10.1080/17445647.2020.1837684

Blomeier D., Scheibner C., Forke H., 2008. *Facies arrangement and cyclostratigraphic architecture of a shallow-marine, warm-water carbonate platform: The Late Carboniferous Ny Friesland Platform in eastern Spitsbergen (Pyefjellet Beds, Wordiekammen Formation, Gipsdalen Group).* Facies, 55, 291-324. https://doi.org/10.1007/s10347-008-0163-3

Brancaccio L., Castiglioni G.B., Chiarini E., Cortemiglia G., D'Orefice M., Dramis F., Graciotti R., La Posta E., Lupia Palmieri E., Onorati G., Panizza M., Pannuzi L., Papasodaro F., Pellegrini G.B., 1994. *Carta Geomorfologica d'Italia - 1:50.000. Guida al rilevamento.* Quaderni del Servizio Geologico Nazionale s. III, 4, 42 pp.

Brückner H., Schellmann G., 2003. *Late Pleistocene and Holocene Shorelines of Andréeland, Spitsbergen (Svalbard): Geomorphological Evidence and Palaeo-Oceanographic Significance.* Journal of Coastal Research, 19 (4), 971-982.

Buer S.F., Hiesinger H., Hauber E., Johnsson A., Bernhardt H., 2019. *Sorted stone circles on Svalbard - an analog study for Mars.* 50th Lunar and Planetary Science Conference 2019, (2132), 10-11.

Campobasso C., Carton A., Chelli A., D'Orefice M., Dramis F., Graciotti R., Guida D., Pambianchi G., Peduto F., Pellegrini L., 2018. *Carta Geomorfologica d'Italia - 1:50.000.* Quaderni del Servizio Geologico Nazionale s. III, 13 (1).

Carado A., 1969. *Carte géomorphologique de reconnaissance de la presqu'île de Brögger (Spitzberg).* Service de documentation et de cartographie géographiques du C.N.R.S.

Carton A., Abbà T., Bondesan A., Fontana A., Mozzi P., Surian N., Zanoner T., Breda A., Massironi M., Preto N., Zampieri D., 2021. *Geomorphological map of the San Pellegrino Pass (Dolomites, Northeastern Italy).* Geografia Fisica e Dinamica Quaternaria, 44, 99-121. https://doi.org/10.4461/GFDQ.2021.44.9

Cottier F., Tverberg V., Inall M., Svendsen H., Nilsen F., Griffiths C., 2005. *Water mass modification in an Arctic fjord through cross-shelf exchange: The seasonal hydrography of Kongsfjorden, Svalbard.* Journal of Geophysical Research: Oceans, 110 (C12). https://doi.org/10.1029/2004JC002757

Etzelmüller B., Sollid J.L., 1991. *The role of weathering and pedological processes for the development of sorted circles on Kvadehuksletta, Svalbard - A short report.* https://doi.org/https://doi.org/10.3402/polar.v9i2.6790

Farnsworth W.R., Allaart L., Ingólfsson Ó., Alexanderson H., Forwick M., Noormets R., Retelle M., Schomacker A., 2020. *Holocene glacial history of Svalbard: Status, perspectives and challenges.* Earth-Science Reviews, 208, 103249. https://doi.org/10.1016/j.earscirev.2020.103249

Forman S.L., Miller G.H., 1984a. *Time-Dependent Soil Morphologies and Pedogenic Processes on Raised Beaches, Bröggerhalvöya, Spitsbergen, Svalbard Archipelago.* Arctic and Alpine Research, 16 (4), 381-394. https://doi.org/10.1080/00040851.1984.12004429

Forman S.L., Miller G.H., 1984b. *Time-dependent soil morphologies and pedogenic processes on raised beaches, Broggerhalvoya, Spitsbergen, Svalbard archipelago.* Arctic & Alpine Research, 16 (4), 381-394. https://doi.org/10.2307/1550900

Forman S.L., Mann D.H., Miller G.H., 1987. *Late Weichselian and Holocene relative sea-level history of Bröggerhalvöya, Spitsbergen.* Quaternary Research, 27 (1), 41-50. https://doi.org/10.1016/0033-5894(87)90048-2

Forman S.L., Lubinski D.J., Ingólfsson Ó., Zeeberg J.J., Snyder J.A., Siegert M.J., Matishov G.G., 2004. *A review of postglacial emergence on Svalbard, Franz Josef Land and Novaya Zemlya, northern Eurasia.* Quaternary Science Reviews, 23 (11), 1391-1434. https://doi.org/10.1016/j.quascirev.2003.12.007

Gabrielsen R., Kløvjan O.S., Haugsbø H., Midbøe P., Nøttvedt A., Rasmussen E., Skott P., 1992. *A structural outline of Forlandsundet Graben, Prins Karls Forland, Svalbard.* Norsk Geologisk Tidsskrift, 72, 105-120.

Gilbert G.L., Instanes A., Sinitsyn A.O., Aalberg A., 2019. *Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard.* AIMS Geoscience, 5 (4), 868-885. https://doi.org/10.3934/geosci.2019.4.868

Gilichinsky D., Rivkina E., Shcherbakova V., Laurinavichuis K., Tiedje J., 2003. *Supercooled water brines within permafrost - An unknown ecological niche for microorganisms: A model for astrobiology.* Astrobiology, 3 (2), 331-341. https://doi.org/10.1089/153110703769016424

Gooseff M.N., Barrett J.E., Levy J.S., 2013. *Shallow groundwater systems in a polar desert, McMurdo Dry Valleys, Antarctica.* Hydrogeology Journal, 21 (1), 171-183. https://doi.org/10.1007/s10040-012-0926-3

Gruppo Nazionale Geografia Fisica e Geomorfologia CNR, 1986. *Ricerche geomorfologiche nell'alta Val di Peio (Gruppo del Cevedale).* Geografia Fisica e Dinamica Quaternaria, 9, 137-191.

Hanken N.-M., Nielsen J.K., 2013. *Upper Carboniferous-Lower Permian* Palaeoaplysina *build-ups on Svalbard: the influence of climate, salinity and sea-level.* Geological Society, London, Special Publications, 376 (1), 269-305. https://doi.org/10.1144/SP376.17

Harland W.B., Horsfield W.T., 1974. *West Spitsbergen Orogen.* Geological Society, London, Special Publications, 4 (1), 747-755. https://doi.org/10.1144/GSL.SP.2005.004.01.46

Hauber E., Reiss D., Ulrich M., Preusker F., Trauthan F., Zanetti M., Hiesinger H., Jaumann R., Johansson L., Johnsson A., Van Gasselt S., Olvmo M., 2011. *Landscape evolution in Martian mid-latitude regions: insights from analogous periglacial landforms in Svalbard.* Geological Society, London, Special Publications, 356, 111-131. https://doi.org/10.1144/SP356.7

Henriksen M., Alexanderson H., Landvik J.Y., Linge H., Peterson G., 2014a. *Dynamics and retreat of the Late Weichselian Kongsfjorden ice stream, NW Svalbard.* Quaternary Science Reviews, 92, 235-245. https://doi.org/10.1016/j.quascirev.2013.10.035

Henriksen M., Alexanderson H., Landvik J.Y., Linge H., Peterson G., 2014b. *Dynamics and retreat of the Late Weichselian Kongsfjorden ice stream, NW Svalbard.* Quaternary Science Reviews, 92, 235-245. https://doi.org/10.1016/J.QUASCIREV.2013.10.035

Hjelle A., Piepjohn K., Saalmann K., Ohta Y., Salvigsen O., Thiedig F., Dallmann W., 1999. *Geological Map of Svalbard 1:100,000.* Sheet A7G Kongsfjorden.

Irrgang A.M., Bendixen M., Farquharson L.M., Baranskaya A.V., Erikson L.H., Gibbs A.E., Ogorodov S.A., Overduin P.P., Lantuit H., Grigoriev M.N., Jones B.M., 2022. *Drivers, dynamics and impacts of changing Arctic coasts*. Nature Reviews Earth & Environment, 3, 39-54. https://doi.org/10.1038/s43017-021-00232-1

Iwahana G., Cooper Z.S., Carpenter S.D., Deming J.W., Eicken H., 2021. *Intra-ice and intra-sediment cryopeg brine occurrence in permafrost near Utqiaġvik (Barrow)*. Permafrost and Periglacial Processes, 32 (3), 427-446. https://doi.org/10.1002/ppp.2101

Johannessen E.P., Steel R.J., 1992. *Mid-Carboniferous extension and rift-infill sequences in the Billefjorden Trough, Svalbard*. Norsk Geologisk Tidskkrift, 72, 35-48.

Kasprzak M., 2020. *Seawater intrusion on the Arctic Coast (Svalbard): The concept of onshore-permafrost wedge*. Geosciences, 10, 349. https://doi.org/10.3390/geosciences10090349

Kavan J., 2020. *Post-Little Ice Age Development of Coast in the Locality of Kapp Napier, Central Spitsbergen, Svalbard Archipelago*. Marine Geodesy, 43 (3), 234-247. https://doi.org/10.1080/01490419.2019.1674429

Klemsdal T., 1986. *Lagoons along the coast of the Svalbard archipelago and the island of Jan Mayen*. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 40 (1), 37-44. https://doi.org/10.1080/00291958608552154

Landvik J., Brook E., Gualtieri L., Raisbeck G., Salvigsen O., Yiou F., 2003. *Northwest Svalbard during the last glaciation: Ice-free areas existed*. Geology, 31, 905-908. https://doi.org/10.1130/G19703.1

Lehmann F., Berger R., Brauchle J., Hein D., Meissner H., Pless S., Strackenbrock B., Wieden A., 2011. *MACS - Modular Airborne Camera System for Generating Photogrammetric High-Resolution Products*. Photogrammetrie - Fernerkundung - Geoinformation, 435-446. https://doi.org/10.1127/1432-8364/2011/0096

Loeng H., 1991. *Features of the physical oceanographic conditions of the Barents Sea*. Polar Research, 10 (1), 5-18. https://doi.org/10.3402/polar.v10i1.6723

Lyberis N., Manby G., 1993. *The origin of the West Spitsbergen Fold Belt from geological constraints and plate kinematics: Implications for the Arctic*. Tectonophysics, 224 (4), 371-391. https://doi.org/10.1016/0040-1951(93)90039-M

Mangold N., 2005. *High latitude patterned grounds on Mars: Classification, distribution and climatic control*. Icarus, 174 (2), 336-359. https://doi.org/10.1016/j.icarus.2004.07.030

Miller G.H., Sejrup H.P., Lehman S.J., Forman S.L., 1989. *Glacial history and marine environmental change during the last interglacial-glacial cycle, western Spitsbergen, Svalbard*. Boreas, 18 (3), 273-296. https://doi.org/10.1111/j.1502-3885.1989.tb00403.x

Nicholson F., 1979. *Permafrost spatial and temporal variations near Schefferville, Nouveau-Québec*. Géographie physique et Quaternaire, 33 (3-4), 265-277. https://doi.org/10.7202/1000363ar

Panizza M., Corsini A., Ghinoi A., Marchetti M., Pasuto A., Soldati M., 2011. *Explanatory notes of the Geomorphological map of the Alta Badia valley (Dolomites, Italy)*. Geografia Fisica e Dinamica Quaternaria, 34 (1), 105-126.

Paquette M., Fortier D., Vincent W.F., 2018. *Hillslope water tracks in the High Arctic: Seasonal flow dynamics with changing water sources in preferential flow paths*. Hydrological Processes, 32 (8), 1077-1089. https://doi.org/10.1002/hyp.11483

Pavlova O., Gerland S., Hop H., 2019. *Changes in Sea-Ice Extent and Thickness in Kongsfjorden, Svalbard (2003-2016)*. In: Hop H., Wiencke C. (Eds), The Ecosystem of Kongsfjorden, Svalbard. Springer International Publishing, Cham, 105-136. https://doi.org/10.1007/978-3-319-46425-1_4

Rotem D., Lyakhovsky V., Christiansen H.H., Harlavan Y., Weilstein Y., 2023. *Permafrost saline water and Early to mid-Holocene permafrost aggradation in Svalbard*. The Cryosphere, 17, 3363-3381. https://doi.org/10.5194/tc-17-3363-2023

Saalmann K., Thiedig F., 2001. *Tertiary West Spitsbergen fold and thrust belt on Brøggerhalvøya, Svalbard: Structural evolution and kinematics*. Tectonics, 20 (6), 976-998. https://doi:10.1029/2001TC900016

Saalmann K., Thiedig F., 2002. *Thrust tectonics on Brøggerhalvøya and their relationship to the Tertiary West Spitsbergen fold-and-thrust belt*. Geological Magazine, 139 (1), 47-72. https://doi.org/10.1017/S0016756801006069

Saloranta T.M., Haugan P.M., 2001. *Interannual variability in the hydrography of Atlantic water northwest of Svalbard*. Journal of Geophysical Research, Oceans, 106 (C7), 13931-13943. https://doi.org/10.1029/2000JC000478

Salvatore M.C., Bertocchini N., Gennaro S., Baroni C., 2021. *Geomorphological map of Valnontey (Gran Paradiso Group, Western Alps, Italy)*. Geografia Fisica e Dinamica Quaternaria, 44, 197-213. https://doi.org/10.4461/GFDQ.2021.44.15

Salvigsen O., Nydal R., 1981. *The Weichselian glaciation in Svalbard before 15,000 B.P.**. Boreas, 10 (4), 433-446. https://doi.org/10.1111/j.1502-3885.1981.tb00507.x

Salvigsen O., Osterholm H., 1982. *Radiocarbon dated raised beaches and glacial history of the northern coast of Spitsbergen, Svalbard*. Polar Research, 1982 (1), 97-115. https://doi.org/10.3402/polar.v1982i1.7000

Stephani E., Jones B., Stephani E., Drage J., Kanevskiy M., Miller D., Jones B.M.,2020. *Taliks, cryopegs, and permafrost dynamics related to channel migration, Colville River Delta, Alaska*. Permafrost and Periglacial Processes, 31, 239-254. https://doi.org/10.1002/ppp.2046

Tavakoli S., Gilbert G., Lysdahl A.O.K., Frauenfelder R., Forsberg C.S., 2021. *Geoelectrical properties of saline permafrost soil in the Adventdalen valley of Svalbard (Norway), constrained with in-situ well data*. Journal of Applied Geophysics, 195, 104497. https://doi.org/10.1016/j.jappgeo.2021.104497

Thiedig F., Saalmann K., Piepjohn K., 2001. *Explanatory notes to the Geological Map of Brøggerhalvøya and Blomstrandhalvøya 1:40,000*. Geologisches Jahrbuch, B91, 25-51.

Tolgensbakk, J., Sollid, J.L., 1987. *Kvadehuksletta, Geomorfologi og Kvartaergeologi*. Norsk Polarinstitutt, University of Oslo.

Torsvik T., Albretsen J., Sundfjord A., Kohler J., Sandvik A.D., Skarðhamar J., Lindbäck K., Everett A., 2019. *Impact of tidewater glacier retreat on the fjord system: Modeling present and future circulation in Kongsfjorden, Svalbard*. Estuarine, Coastal and Shelf Science, 220, 152-165. https://doi.org/10.1016/j.ecss.2019.02.005

Ulrich M., Wagner D., Hauber E., de Vera J.-P., Schirrmeister L., 2012. *Habitable periglacial landscapes in Martian mid-latitudes*. Icarus, 219 (1), 345-357. https://doi.org/10.1016/J.ICARUS.2012.03.019

Washburn A.L., 1956. *Classification of Patterned Ground and Review of Suggested Origins*. Bulletin of the Geological Society of America, 67 (7), 823-866. https://doi.org/10.1130/0016-7606(1956)67[823:COPGAR]2.0.CO;2

Wojcik R., Palmtag J., Hugelius G., Weiss N., Kuhry P., 2019. *Land cover and landform-based upscaling of soil organic carbon stocks on the Brøgger Peninsula, Svalbard*. Arctic, Antarctic, and Alpine Research, 51 (1), 40-57. https://doi.org/10.1080/15230430.2019.1570784

(Ms. received 22 February 2024, accepted 02 May 2024)